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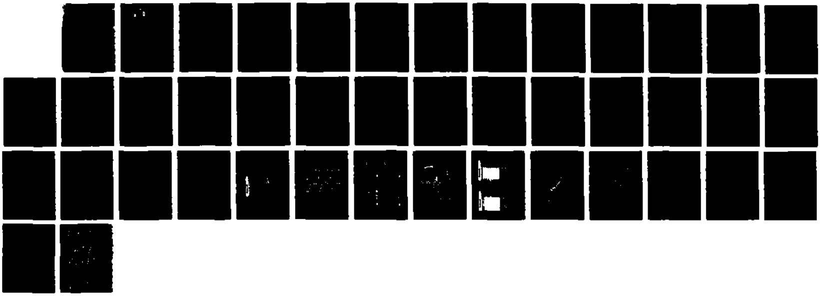

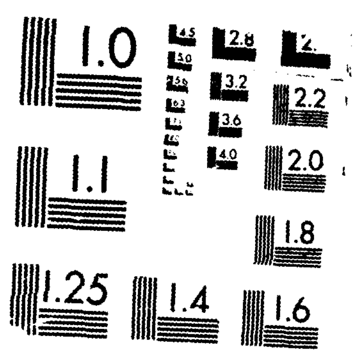

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Binning Spectral Images in a Charge-Coupled Device (CCD)

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BRIEF

This article focuses on the use of binning in a two-dimensional charge-coupled device (CCD) for increasing the sensitivity and dynamic range of spectroscopic measurements. Practical factors related to binning spectral images including spectral line orientation, blooming, and readout speed are also discussed.

ABSTRACT

A charge-coupled device (CCD) can selectively combine photogenerated charge from several detector elements into a single charge packet by a charge readout mode called binning. This article focuses on the use of charge binning in a two-dimensional CCD for increasing the sensitivity and dynamic range of spectroscopic measurements. Binning allows the effective detector element size to be matched to the size of the slit image. Equations describing the signal-to-noise ratio and dynamic range of the binned readout of spectral lines are developed. Results of binning to increase the sensitivity of atomic emission and molecular fluorescence measurements are presented. An intraspectral dynamic range of 500,000 is achieved by mixing binned and normal readout modes of a Hg atomic emission spectrum. Practical factors related to binning spectral images including spectral line orientation, readout speed, and blooming are discussed.

Charge-coupled devices (CCDs) are the most sensitive array detector available for low-light level scientific imaging applications. The factors responsible for the sensitivity of CCDs include high quantum efficiency, the ability to integrate charge for hours, negligible dark current and, most importantly, an extremely low detector noise (1-3). Although primarily used for imaging, there is a great deal of interest in the use of CCDs as detectors for spectroscopy in the near-infrared, visible, ultraviolet and x-ray regions (4-6).

The physical format of two-dimensional CCD detectors is designed primarily for imaging applications and not for spectroscopy. The height to width aspect ratio a single detector element is poorly matched to the images of a slit normally encountered in spectroscopy. Most CCD detector elements range in size from 6.8 by 6.8 μm to 30 by 30 μm (6); whereas the size of spectrograph slits range in size from 10 to 500 μm wide and 1 to 10 mm tall. A spectral line focused onto a two-dimensional CCD typically covers a hundred or more detector elements. The measurement of a single wavelength requires that photogenerated charge from the detector elements illuminated by the slit image be summed together.

The manner of summing photogenerated charge from several detector elements directly effects the signal-to-noise ratio (S/N) and dynamic range of the measurement of spectral line intensities. The method of summation can be either digital or analog. Digital summation is accomplished by individually reading out and digitizing each charge packet, followed by storing and summing the digitized intensities in a computer. Analog summation is performed by physically combining the photogenerated charge packets into a single charge packet in a process called binning. The binning of charge packets reduces the number of detector read operations

needed to measure a group of charge packets. Because the detector read noise is independent of signal level, reducing the number of reads reduces the overall detector noise associated with the measurement of a group of charge packets comprising a spectral line. Binning is a unique readout mode that is not possible with X-Y addressed detectors such as photodiode arrays and charge-injection devices. Binning allows the effective detector element size to be dynamically altered during the readout process. Because the signal is proportional to the amount of charge transferred to the output node, the output sensitivity, dV/dq, is independent of binning. Binning serves to collect and noiselessly compress photogenerated charge from a relatively large area of the CCD.

The utility of binning in increasing the S/N of weak spectral images was first recognized by astronomers (7,8) and has since become a common technique in many areas of low light level spectroscopy (9,10). Although binning in scientific CCD applications is now fairly widespread, a careful analysis of the theoretical and practical aspects of binning does not exist. This paper presents a detailed description of binning and its significance in spectroscopic applications.

CHARGE TRANSFER AND BINNING IN A CCD

A brief description of the structure and normal operation of a two-dimensional CCD is presented to provide a framework for the discussion of binning. More complete descriptions of CCDs are found in References 1-5.

Normal readout of a two-dimensional CCD

The two-dimensional CCD used in these studies is comprised of a parallel register containing 512 rows and 320 columns, a 320 element serial

register, an output node, and an on-chip amplifier as shown in Figure 1. The terms parallel and serial are used in this article to refer to the direction of charge transfer and the orientation of an image on a CCD. Referring to Figure 1, the parallel direction is vertical and the serial direction is horizontal. The parallel register integrates photogenerated charge from an image focussed onto the CCD. Vertical channel stop diffusions create potential barriers preventing charge from moving horizontally in the parallel register from one column to the next. Parallel register electrodes running horizontally across the parallel register control the movement of charge packets in the columns.

Photogenerated charge from an image is read in a series of steps, starting with the shifting of charge in the parallel register toward the serial register by one row, as shown in Figure 1. The parallel shift transfers charge from the top row of the parallel register into the serial register. The charge packets in the serial register are then sequentially shifted to the output node and measured. For every parallel transfer of charge in this CCD, there are 320 serial transfers. The process of shifting charge in the parallel register, followed by shifting charge in the serial register to the output node is repeated until every row of charge has been transferred to the serial register and read out.

The signal at the input of the on-chip amplifier is the voltage change generated by the transfer of charge onto the output-node. The CCD's ability to transfer a charge packet to a low capacitance output node avoids the relatively high capacitance sensing structure associated with an X-Y addressed array detector, such as photodiode arrays and charge-injection devices. The output node capacitance of 70 femptofarads (11) results in an input signal to the on-chip amplifier of 2.3 μV/e- that is measured easily

with minimal amplification. It is important to note that it is the capacitance of the output node and not the detector element that determines the output sensitivity, dV/dq, of the CCD signal. The output sensitivity depends only on the amount of charge transferred onto the output node and is independent of the area of silicon involved in collecting photogenerated charge.

Serial binning of charge

Charge is binned by combining charge packets contained in two or more adjacent potential wells into a single potential well during charge readout. Adjacent charge packets in both the serial and parallel directions can be combined. Charge is binned serially in the output node during the transfer of charge in the serial register. Two-fold serial binning is illustrated in Figure 2. The digital image from a two-fold serially binned readout has half the serial resolution of an unbinned image. Each datum represents the sum of two adjacent charge packets.

Serial binning of charge from any number of adjacent detector elements is possible, including binning all of the charge packets in the serial register into a single charge packet. Binned and non-binned readout of groups of charge packets can be mixed in any combination. The only limitation to binning charge from several detector elements is that the level of the binned charge packet does not exceed the charge holding capacity of the output node or the on-chip amplifier. Exceeding the charge capacity of any potential well in a CCD causes the excess charge to spill into adjacent potential wells, a condition known as "blooming" that is disastrous when making quantitative spectral measurements (4).

Parallel binning of charge

Parallel binning is similar to serial binning except that rows of charge packets are combined instead of individual charge packets. Three-fold parallel binning of charge is illustrated in Figure 3. Parallel binning any number of rows of charge packets into a single row is possible, including binning charge from every row of the parallel register into a single row. Binned and non-binned readout of rows can be mixed in any combination; the number of rows that can be parallel binned is limited only by the charge capacity of the serial register. Because charge packets from an entire row are transferred in parallel, it is not possible to parallel bin a portion of a row.

Two-dimensional binning

Binning of charge in two-dimensions is possible from any rectangular group of detector elements. Binning in both dimensions is accomplished by combining serial and parallel binning. Once again, the only limitation to the number of charge packets that can be binned is the finite charge capacities of the serial register, the output node, and the on-chip amplifier.

EXPERIMENTAL SECTION

The CCD based spectrograph constructed in our laboratories is shown in Figure 4. The fluorescence excitation source is a mercury pen lamp (Ultraviolet Products Inc.) filtered with a 250 nm bandpass interference filter and focussed onto a quartz cuvette. The fluorescence emission is collected at right angles to the excitation and focused onto the entrance slit of the 200 mm focal length, f/3 spectrograph (Instruments SA, Model UFS 200). The Hg emission spectrum from the pen lamp is measured by focusing the light

from the mercury pen lamp directly onto the slits of the spectrograph. The 200 groove/mm grating disperses light across the CCD at 23 nm per mm (0.7 nm per detector element). A computer controlled shutter controls the exposure time and blocks the light during readout.

The detector employed in these investigations is a 320 by 512 element RCA-SID501EX backside-illuminated CCD with 30 by 30 μm detector elements. The on-chip amplifier noise associated with measuring a single charge packet is 50 electrons at the 50 kHz data rate used in these studies. The CCD is housed in a liquid nitrogen cryostat and cooled to 123 +K to reduce dark current to negligible levels. The CCD detector system (Model CH181, Photometrics Ltd., Tucson, AZ) allows full image, subarray and binned readout modes. Charge packets are measured using the correlated double sampling technique (12), and digitized to 14 bits. The gain of the CCD electronics is 35 e-/digital number. A more detailed description of the instrument is given in Reference 13.

RESULTS AND DISCUSSION

When binned readout modes are employed there is no longer a one to one correspondence between a CCD detector element and an element of the digitized image. The relationship between the CCD format and the digital image format as a function of binning parameters is defined in the following sections. Table I illustrates the relationship between the CCD image and the digital image by listing several parameters of an image acquired with seven different readout modes of the RCA-SID501EX CCD.

CCD format and image format

The area of the CCD corresponding to one element of the image, A_{image}, increases with binning according to:

$$A_{image} = A_{ccd} B_s B_p, \qquad (1)$$

where A_{ccd} is the area of a single detector element of the CCD, and B_p is the binning factor in the parallel direction, and B_s is the binning factor in the serial direction. A_{image} increases 160,000 fold in going from a normal to a completely binned readout mode, as noted by comparing modes 1 and 7 of Table I.

The digitized image format is reduced by binning according to:

$$C_{image} \text{ by } R_{image} = C_{ccd}/B_s \text{ by } R_{ccd}/B_p, \qquad (2)$$

where C_{image} and R_{image} are the number of columns and rows of the digitized image respectively, and C_{ccd} and R_{ccd} are the number of columns and rows of the CCD respectively. Binning also reduces the total amount of information transferred to and stored by the computer for each image according to:

$$Z_{image} = Z_{ccd} / B_p B_s, \qquad (3)$$

where Z_{image} is the number of elements in the digital image, and Z_{ccd} is the number of detector elements in the CCD.

Normal and binned image readout rates

Binning decreases the time required to read out an image compared to a normal readout. The amount by which the readout time is decreased depends on the degree of binning, the parallel and serial transfer rates, and the time required for the correlated double sampling and digitization of a charge packet.

The time required for reading out charge from the entire CCD is:

Readout time $= R_{ccd}\, T_p + Z_{ccd}\, T_s/B_p + Z_{ccd} T_d/B_p B_s$ (4)

where T_p and T_s are the times required for one transfer of charge in the parallel and serial directions respectively, and T_d is time required to perform the double correlated sampling and digitization of a charge packet. For the CCD detector system employed in these studies, using relatively slow clock rates to insure optimal charge transfer effeciency, T_s is 2 μs, T_p is 15 μs, and T_d is 20 μs. Because the majority of the readout time for an unbinned image is devoted to digitizing charge packets to 14 bits, binning significantly decreases the time required to read the charge from the CCD. For example, the read times range from 3.6 s for an unbinned image to 8.3 ms for a fully binned image. Because parallel binning decreases the number of serial transfers in addition to the number of digitizations, it results in a shorter read time than equivalent serial binning. A comparison of the readout times of modes 3 and 5 of Table I shows the parallel binned mode is more than twice as fast as equivalent binning in the serial direction.

Special binned readout modes of interest in spectroscopy

The names attached to several of the readout modes in Table I indicate several uses of binned readout modes in spectroscopy. The "single element" readout mode bins charge from the entire CCD into a single charge packet. This reduces the 320 by 512 element CCD to a single channel detector with an active area of 147 mm^2. Modes 4 and 7 are both termed the "linear array mode", because complete binning in either the serial or parallel directions effectively turns the two-dimensional array into a linear array of detector elements having a high height to width aspect ratio. Mode 6 effectively

changes the 320 by 512 element CCD into two 320 element linear arrays, one stacked on top the other. With the proper optics, this CCD binning mode can acquire a sample and blank spectrum simultaneously with a high degree of accuracy. In this true "double beam" mode, both spectra are acquired during one integration period totally eliminating problems caused by source drift. The sample and blank spectra are readout using the same electronics within 16 msec, additionally reducing any electronic drift errors.

SENSITIVITY

A simplified model for the S/N for the measurement of a single photogenerated charge packet in a CCD is:

$$S/N_{\text{single packet}} = S/(S + N_r^2)^{1/2} \qquad (5)$$

where S is the average photogenerated signal integrated in a single detector element and N_r is the read noise introduced by the detector when measuring the intensity of the charge packet. The photon signal is assumed to be noiseless except for shot-noise and the energy of the photons is assumed to be low enough such that only one electron is created per absorbed photon. The read noise of a CCD is largely determined by the noise of the on-chip amplifier and is independent of the signal (3).

S/N of spectral line

The S/N for the measurement of a spectral line that illuminates several detector elements depends on the manner in which the data from the detector elements are summed. The spectral line is measured by reading out each charge packet independently followed by summing the digitized intensities, or by binning all of the charge from a spectral line into a single charge packet and subjecting this binned charge packet to a single digitization.

The total charge measured in both cases is identical; however, the total detector noise contribution to the measurement depends upon the readout method employed.

The S/N for a spectral line measured by reading out charge packets individually and then summing the digitized intensities in computer memory is:

$$S/N_{K\ (\mathrm{normal})} = KS/(KS + KN_r^2)^{1/2}, \qquad \underline{(6)}$$

where K is the number of detector elements illuminated by the spectral line. The S/N for the same spectral line measured by binning K charge packets followed by a single digitization is:

$$S/N_{K\ (\mathrm{binned})} = KS/(KS + N_r^2)^{1/2}. \qquad \underline{(7)}$$

Equation 7 assumes that read noise is independent of binning, a condition that is generally true for most CCDs with moderate binning and integration conditions (14). For spectral measurements using long integration times or high binning factors, the read noise may become dominated by secondary noise sources that are not independent of binning, such as dark current and charge transfer losses. In these situations, binning may no longer achieve the S/N increase predicted in equations 6 and 7.

Equations 6 and 7 differ only in that summing in computer memory subjects the photogenerated charge to the read noise from K reads, but binning subjects the same charge information to the noise from only a single read. For a bright spectral line where $S \gg KN_r^2$, the dominant noise is the photon shot noise and both equations predict approximately the same SNR. However, for a weak spectral line where $KN_r^2 \gg S$, the measurement is

detector noise limited and binning results in a S/N advantage of $\sqrt{K}$. When a CCD is used to detect extremely weak spectral lines that cover several detector elements, the highest possible S/N is realized by binning all of the photogenerated charge from a spectral line into a single charge packet.

Binned readouts of Hg atomic emission lines

The validity of equations 6 and 7 was examined by measuring the S/N of the 404.7 nm Hg emission line from a mercury lamp. The Hg spectrum was dispersed in the parallel orientation described in Figure 5. A 100 μm wide by 3 mm tall slit produced a emission spectrum that covered approximately 100 of the 512 rows of the CCD. The S/N was measured using normal and 100 fold parallel binned readout modes. The integration time varied from .1 to 300 seconds and the line was measured five times for each exposure. A dark exposure of equal integration time was subtracted from each measurement.

The results of the measurements of the 404.6 nm line for normal and binned readout modes is shown in Figure 6. The curved lines are the theoretically predicted S/N based on a read noise of $\sqrt{2}$*50 electrons (the root 2 arises from the two read noises in each measurement of signal - background). Note that at low signal levels, binning improves the S/N by a factor equal to square root of the number of detector elements binned; however, at high signal levels, the S/N for the normal readout mode approaches the binned S/N. The agreement between the predicted and experimental S/N indicates that the read noise in these measurements is largely independent of binning.

Binned readout of anthracene fluorescence spectrum

The role of binning in improving the sensitivity of molecular fluorescence spectra was qualitatively investigated by measuring the the fluorescence spectrum of anthracene. The fluorescence emission from a

10^{-6} molar solution of anthracene in ethanol was dispersed across the CCD in the parallel orientation of Figure 5 for a 1 s integration. The 250 μm by 5 mm slit produced a spectral image covering approximately 160 of the 512 rows of the CCD. The 320 elements/row provided a wavelength coverage of approximately 220 nm at 0.7 nm/detector element and a spectral resolution of 5 nm.

The result of parallel binning along the slit dimension to increase the S/N of the anthracene spectrum is shown in Figure 7. The six spectra are the result of binning and digital summing the charge intensities from the 160 illuminated rows using parallel binning factors of 1X, 2X, 4X, 10X, 40X, and 160X (a binning factor of 1X is a normal readout). For example in the case of 4X binning, the 160 rows of charge were binned 4 fold into 40 rows and read out, followed by the digital summation of the 40 rows. The 40 rows were digitally summed in the computer. Each spectra represents the detection of the same amount of photogenerated charge. The increased S/N achieved by charge binning in the slit dimension is realized at the expense of spatial resolution in the slit dimension; a loss that is insignificant in this example.

The result of binning in the direction of wavelength dispersion on the anthracene spectrum under the same conditions as above is shown in Figure 8. In this case, binning increases the S/N, but at the expense of spectral resolution. The ability to bin in the direction of wavelength dispersion allows the effective detector element size to be altered to match the spectral resolution requirements.

Binning is simply a means of increasing the already excellent sensitivity of a CCD and should be employed whenever advantageous. Even

without employing binned readout modes, CCDs are sensitive spectroscopic detectors compared to other array detectors. For example, the read noise associated with sensing charge from 100 detector elements from the RCA-SID501EX CCD is 50 electrons with binning and 500 electrons without binnning. The 500 electrons of noise is still less than half the detector noise found in a single element of a photodiode array especially made for spectroscopy with a comparable imaging area. (15).

DYNAMIC RANGE

The simple dynamic range (SDR) of a solid state detector is the ratio of the largest to smallest measurable charge packet of a single detector element from a single exposure. The largest measurable charge packet is equal to the full well capacity (FWC) of the parallel register potential well. For this discussion, FWC is defined as the maximum amount of charge containable in a detector element before charge blooms. The smallest measurable charge packet at a S/N of two is approximately equal to twice the detector read noise; therefore:

$$SDR = FWC/2N_r. \qquad (8)$$

Intraspectral dynamic range

The intraspectral dynamic range (ISDR) of an array detector is the ratio of the brightest to weakest spectral line that can be simultaneously measured from a single exposure (15). The ISDR of a CCD used for spectroscopic measurements depends on the SDR, the number of detector elements illuminated by the spectral line, and whether normal or binned readout modes are used.

For a binned readout, the intensity of the weakest spectral line focused onto K detector elements that can be detected at a S/N of 2 is approximately twice the read noise. The intensity of the brightest spectral line uniformly illuminating K detector elements that can be measured by binning depends on the maximum amount of charge that can be binned in the serial register potential wells and the amplifier output node before blooming occurs. The ISDR for a binned readout measurement is:

$$ISDR_{binning} = LFWC/2N_r \qquad (9)$$

where LFWC is the limiting full well capacity of either the serial register or output node. The serial register and output node well capacities of most CCDs are between 2 to 10 times as large as the parallel register well capacities; thus, $ISDR_{binning}$ is greater than the SDR by an equivalent factor. This dynamic range is realized only if the CCD electronics are capable of measuring such a large dynamic range. Low noise CCDs with large full well capacities are beyond the limits of 16 bit analog to digital converters (16).

For a normal readout, the intensity of the weakest spectral line focussed onto K detector elements that can be detected at a S/N of 2 is approximately $2\sqrt{K}$ RN by Eq. 6. The intensity of the strongest measurable spectral line uniformly illuminating K detector elements is K * FWC. The ISDR for a non-binned readout is:

$$ISDR_{normal} = K\ FWC/2\sqrt{K}\ N_r = \sqrt{K}\ SDR. \qquad (10)$$

Dynamic range enhancement by mixed readout mode

Binning and non-binned readout modes in a single exposure can be mixed to increase the ISDR beyond that of the $ISDR_{normal}$. Weak spectral regions are selectively binned in the serial register; all other spectral regions

are read out normally. The intraspectral dynamic range using a mixed readout mode is:

$$ISDR_{mixed} = K\ FWC/2N_r = K\ SDR. \qquad \underline{(11)}$$

Two restrictions apply to the use of a mixed readout mode. First, because charge is shifted in the parallel register before the serial register, a mixed readout mode is only possible when the spectral lines are oriented parallel to the CCD serial register. Second, binning must be limited to spectral lines of low intensity to avoid charge blooming caused by overfilling the output node. This restriction dictates that the approximate intensity of each spectral line be known before it is readout. One method of determining the approximate intensity is to read out the first few charge packets from each spectral line. If the signal is below a predetermined threshold, the remaining charge packets are binned into a single charge packet. If the signal is above the threshold, the remaining charge packets are read out individually.

The SDR and ISDR of the RCA-SID501EX CCD for a slit image that illuminates 100 detector elements is illustrated in <u>Figure 9</u>. Note that the low end of $ISDR_{mixed}$ is set by $ISDR_{binned}$ and the high end is determined by the $ISDR_{non\text{-}binned}$.

The use of selective binning to increase the ISDR of a measurement of the Hg emission spectrum is shown in <u>Figure 10</u>. Light from the Hg pen lamp was focussed onto the 100 μm by 3 mm slits and dispersed across the CCD in the serial orientation of <u>Figure 5</u>. The spectrum illuminated approximately 80 columns of the CCD. Charge from a weak spectral line was serial binned 80 fold and parallel binned 2 fold. Strong emission lines were read out without binning and summed in computer memory. The weakest spectral feature

is the 275.3 nm Hg line at an intensity of 150 photogenerated electrons, or approximately 1 electron per detector element. The most intense spectral feature is the 546.1 nm Hg line with an intensity of approximately 80 million photogenerated electrons, or 500,000 electrons per detector element. The dynamic range of spectral intensities from this single exposure of the CCD to the Hg spectrum is 530,000.

SPECTRAL LINE ORIENTATION

A linear spectrum can be dispersed across a two-dimensional CCD with the spectral lines parallel or perpendicular to the serial register as shown in Figure 5. Each orientation has certain advantages and disadvantages and the optimum orientation depends upon the demands of the particular spectroscopic measurement. The serial orientation allows the mixing of binned and normal readout modes of spectral lines in a single exposure. As discussed in the dynamic range section, mixed readout results in a significant increase in the ISDR of the CCD. The serial orientation for this particular CCD also has the obvious advantage of allowing a broader spectral coverage than the parallel orientation.

Parallel orientation results in a faster readout than serial orientation because it reduces the number of serial transfers. The parallel orientation is also more resistant to cross talk between spectral lines because of the nature of charge blooming. When a detector element in a particular column is filled past saturation, charge spills into adjacent detector elements in the column. The parallel orientation ensures that charge from an intense spectral line that blooms does not spill into other spectral lines. Blooming of charge in the serial orientation would result

in charge from the intense spectral line spilling into adjacent spectral lines.

CONCLUSIONS

This work demonstrates the significant increase in sensitivity, dynamic range, and flexibility possible by binning charge in a CCD used for spectroscopic measurements. Binning dynamically changes the effective detector element size of a two-dimensional CCD to match the optical requirements of conventional spectrographs. Because binning parameters are under computer control, photogenerated charge from detector elements illuminated by the slit image are easily and noiselessly combined into a single charge packet.

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CREDITS

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Image format size, effective detector element area, number of data points per image, and read time for a 512 row by 320 column CCD readout with various bin factors. Terms are defined in the text.

Mode	Binning $B_p \times B_s$	Image format $R_{image} \times C_{image}$	A_{image} (mm^2)	Z	Read time (ms)	Notes
(1)	1 x 1	512 x 320	.0009	163840	3612	normal readout
(2)	4 x 4	128 x 80	.0144	10240	294	4 by 4 mode
(3)	1 x 64	512 x 5	.0576	2560	387	64 fold serial bin
(4)	1 x 320	512 x 1	.2880	512	346	linear array mode
(5)	64 x 1	8 x 320	.0576	2560	64.0	64 fold parallel bin
(6)	256 x 1	2 x 320	.2304	640	21.8	double beam mode
(7)	512 x 1	1 x 320	.4608	320	14.7	linear array mode
(8)	512 x 320	1 x 1	147.5000	1	8.3	single detector mode

FIGURE CAPTIONS

1. Diagram of the RCA-SID501EX CCD showing the method of charge transfer in a two-dimensional CCD. Photogenerated charge from an image is integrated in the parallel register. During charge readout, rows of charge packets are shifted in parallel by the parallel register electrodes. The top row of charge in the parallel register is transferred into the serial register. The serial register then transfers a single row of charge to the output node of the on-chip amplifier. The parallel and serial shifting of charge is repeated until every row is transferred to the serial register and read out.

2. Simplified diagram of two-fold serial binning of charge in the output node of a 4 by 6 element CCD. (1) Photogenerated electrons integrated in parallel register. (2) Charge in the parallel register is shifted upward by one row causing charge from the top row of the parallel register to transfer into the serial register. (3) Charge packet A is transferred into the output node potential well. (4) Charge from detector element B is transferred to the output node and combined with the charge packet A. (5) The combined charge packet is sensed by the on-chip amplifier and the output node potential is reset. (6) Steps 3 and 4 are repeated to bin charge packets C and D. The resulting digitized image has half the serial resolution of an unbinned image.

3. Simplified diagram of three-fold parallel binning of charge in the serial register of a 4 by 6 element CCD. (1) Photogenerated charge packets corresponding to the 4 by 6 image. (2) Charge in the parallel register is shifted upward by one row causing charge from the top row of the parallel register to transfer into the serial register. (3) Charge is parallel shifted again transferring charge from row B into the serial register and combining it with charge from row A. (4) The parallel register is clocked a third time and charge from row C is added to charge from rows A and B in the serial register. The binned charge packets in the serial register are shifted to the ouput node and readout in a normal fashion. Steps 2 - 4 are repeated to bin charge from rows D, E, and F into a single row. The resulting digitized image has one-third the parallel resolution of an unbinned image.

4. Block diagram of CCD spectrograph. Hg pen lamp is placed at A when used as a molecular fluorescence excitation source and at B when used as an atomic emission source.

5. Parallel and serial orientations of a linear spectrum dispersed across a two-dimensional CCD. The spectral lines are the image of the slit focussed onto the CCD.

6. Log signal to noise (S/N) versus log signal (S) for 404.7 nm Hg emission line illuminating 100 detector elements. Open circles are from 100 fold binned readout and closed circles are from normal readout. Top line is the theoretically predicted S/N using Eq. 3 for 100 fold binned readout and a

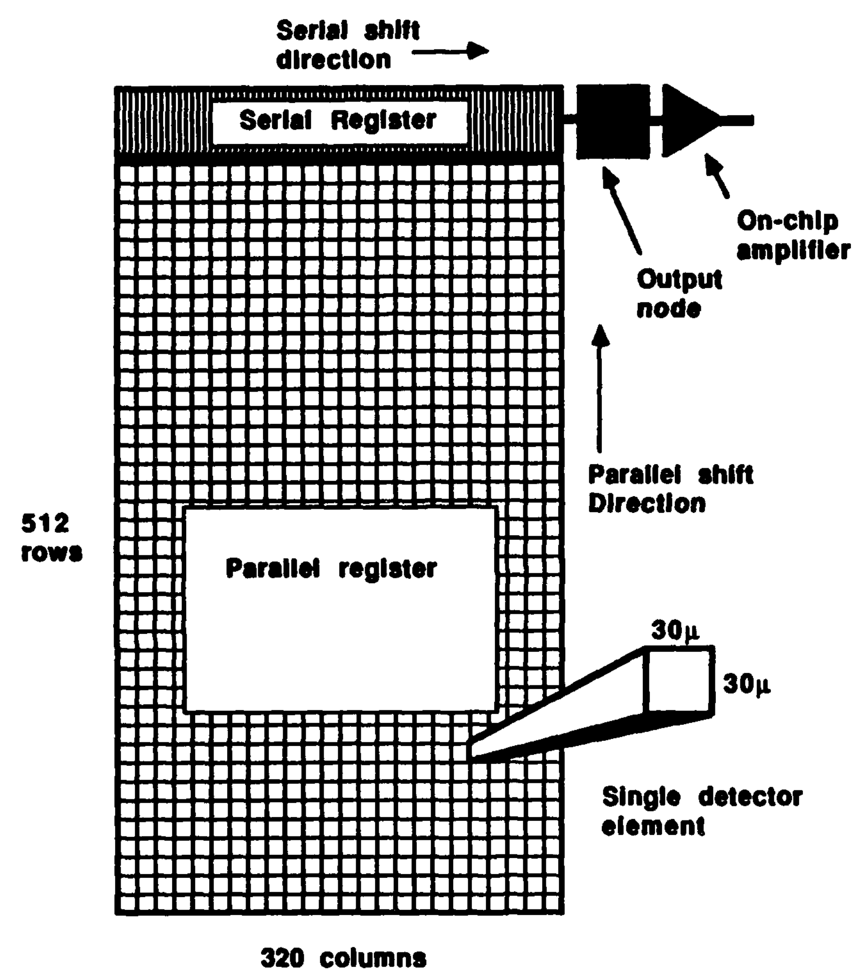
detector read noise of 71 e-. Bottom line is the theoretically predicted S/N using Eq. 2 for normal readout and a detector read noise of 71 e-.

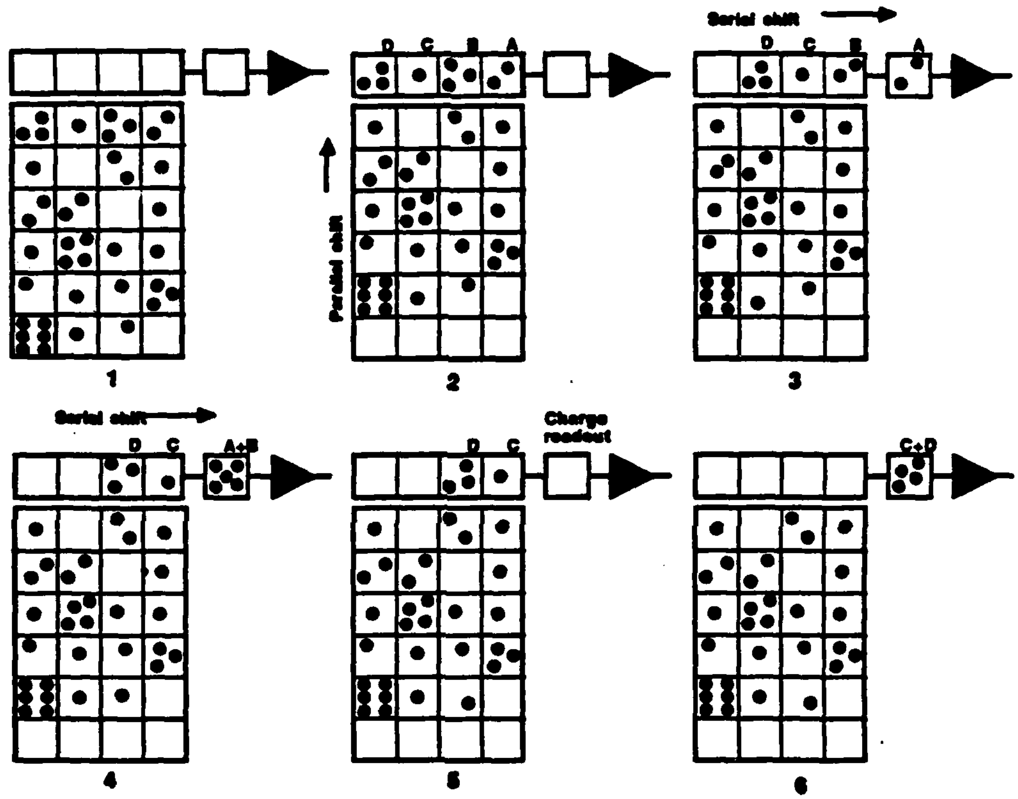
7. Fluorescence emission spectra of 10^{-6}M anthracene for a 1 second exposure with different parallel binning parameters. Charge was binned in the slit dimension of the spectral image. Each spectrum is the result of digital and analog (binning) summing of charge information from 160 rows of the CCD. 1X - digital summation of 160 digitized rows; 2X - digital summation of 80, 2-fold binned rows; 4X - digital summation of 40, 4-fold binned rows, 10X - digital summation of 16, 10-fold binned rows; 40X - digital summation of 4, 40-fold binned rows; 160X - single 160-fold binned row. Spectra are offset for clarity. Binning increases the S/N by reducing the number of digitizations. The intensity at 400 nm is approximately 8000 photogenerated electrons, or 50 electrons per CCD detector element.

8. Fluorescence emission spectra of 10^{-6}M anthracene for a 1 second exposure with 1 to 16 fold binning in the direction of wavelength dispersion (serial). The spectra are also binned 160 fold in the slit (parallel) dimension. The intensity of spectra 2X - 16X are normalized to 1X spectrum (normal readout) by dividing by the serial binning factor. Note the slight increase in S/N at the expense of wavelength resolution. Binning factors up to 4x are tolerated without a serious loss of spectral resolution because of the relatively broad molecular fluorescence spectral features and the 5 nm (7 detector element) spectral resolution of the spectrograph.

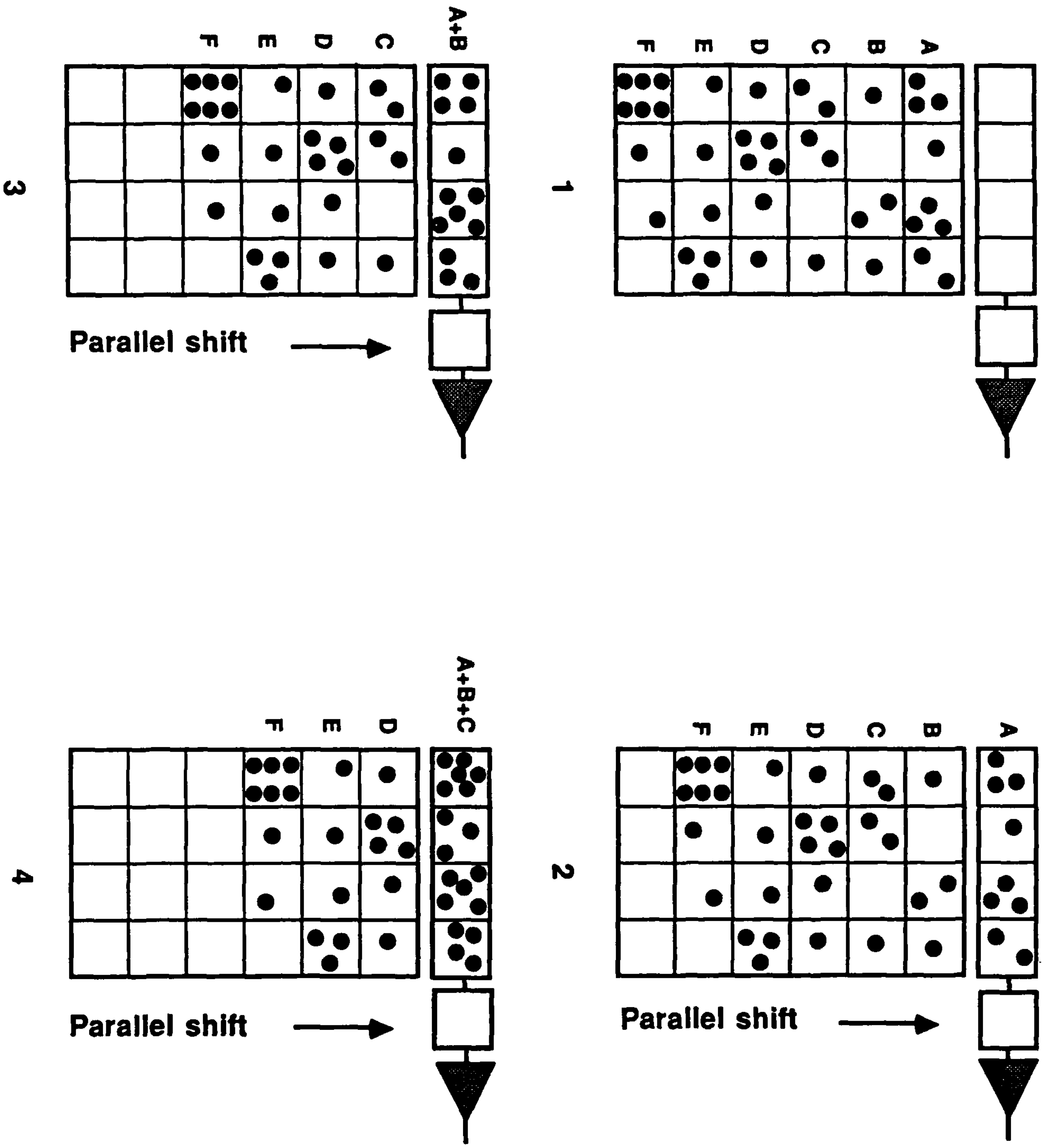
9. The SDR and ISDR of the RCA-SID501EX CCD for a spectral line illuminating 100 detector elements, based on equations 8-11 and a parallel register full well capacity of 500,000 electrons, serial register full well capacity of 1,000,000 electrons, and a read noise of 50 electrons.

10. Hg spectrum from using a mixed readout mode. Inset is the spectral region from 270 to 360 nm expanded 100 fold. Charge from selected weak spectral lines are binned 80 by 2 fold into a single charge packet. Charge from intense spectral lines are readout normally. The minimum detectable emission line at 275.3 nm is 150 electrons, the maximum at 546.1 nm is over 80 million electrons. The dynamic range is 530,000 for a single exposure of the CCD to an atomic emission spectrum.

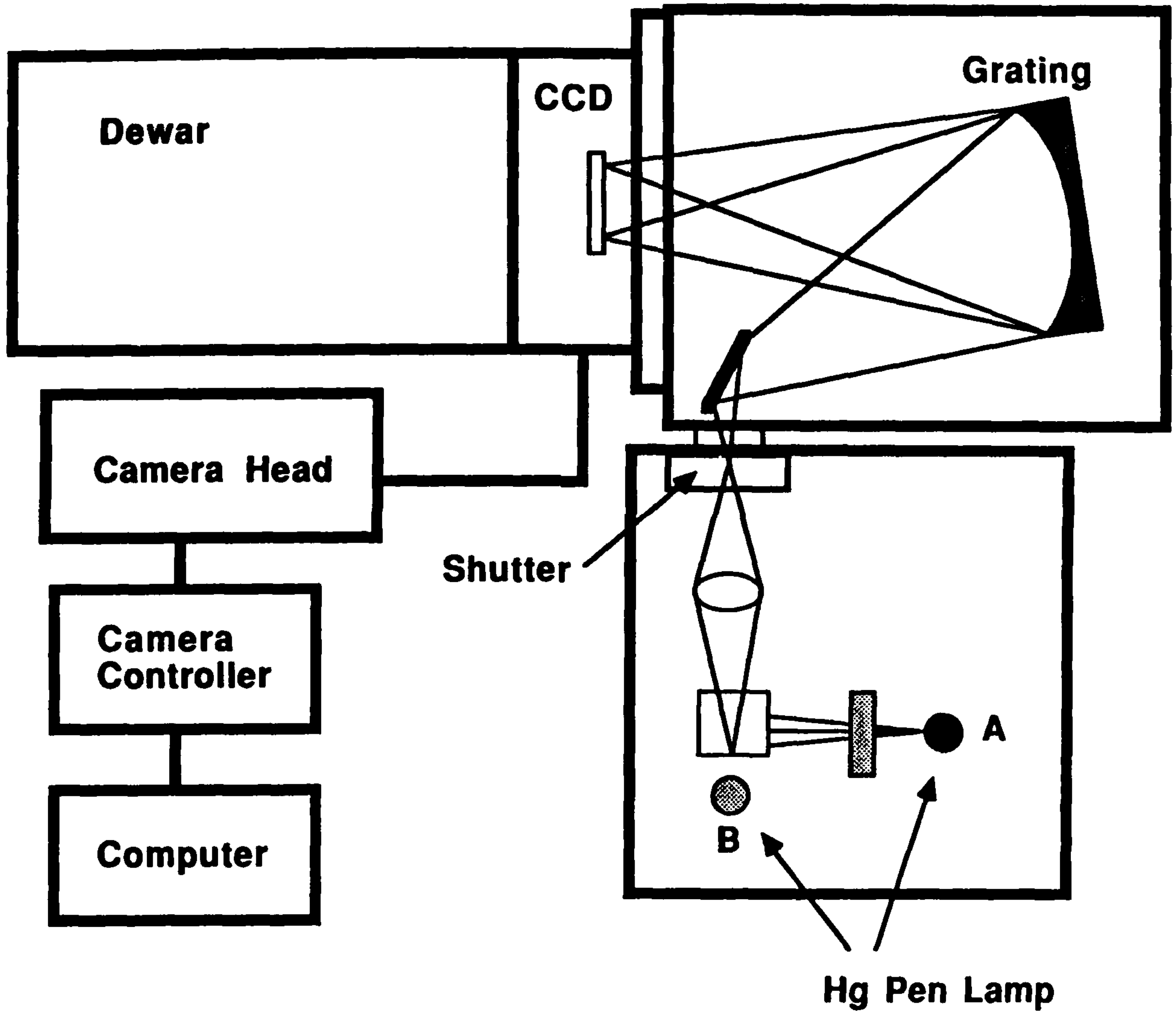

Serial shift direction
Serial Register
On-chip amplifier
Output node
Parallel shift Direction
512 rows
Parallel register
30μ
30μ
Single detector element
320 columns

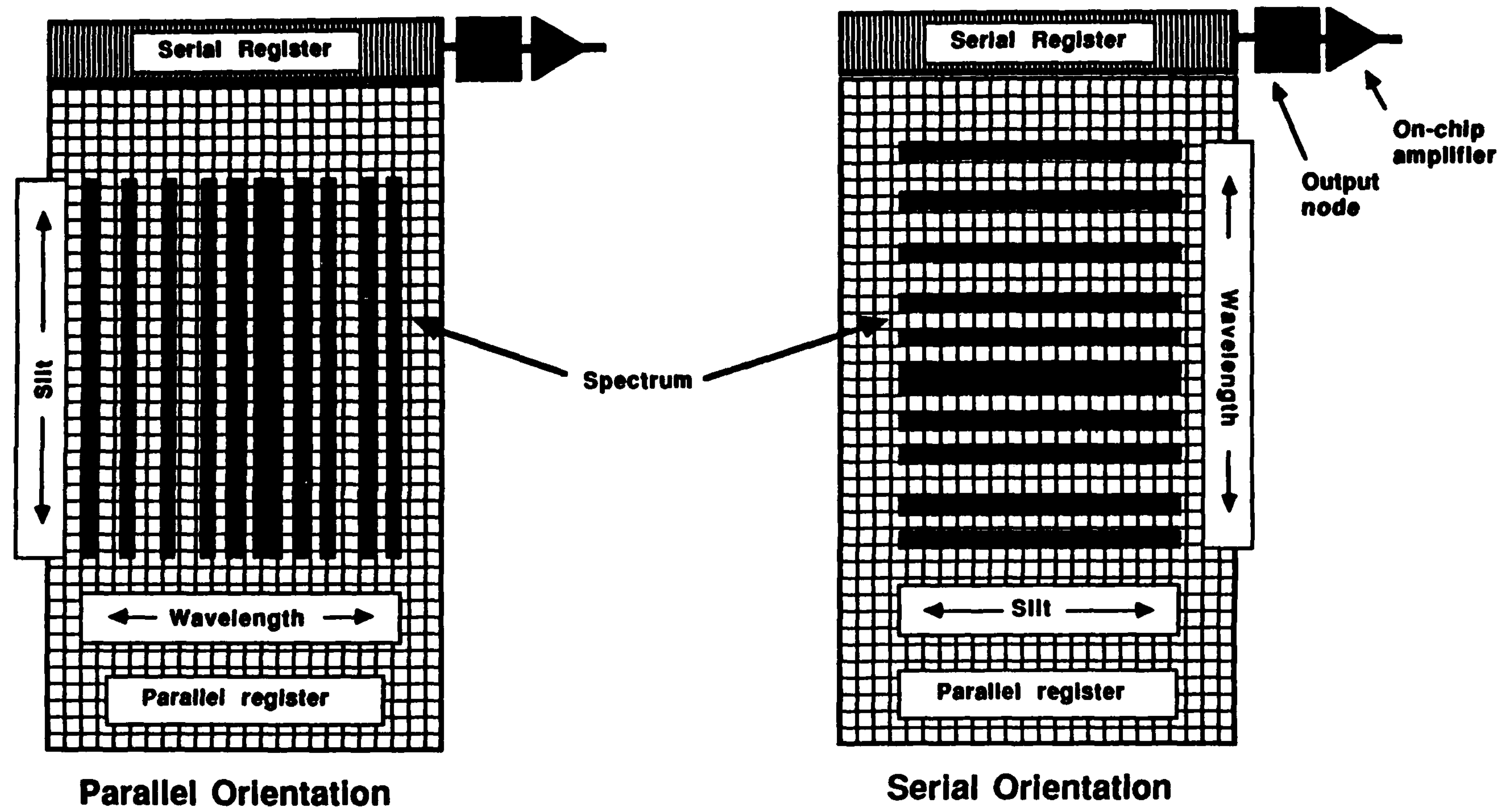


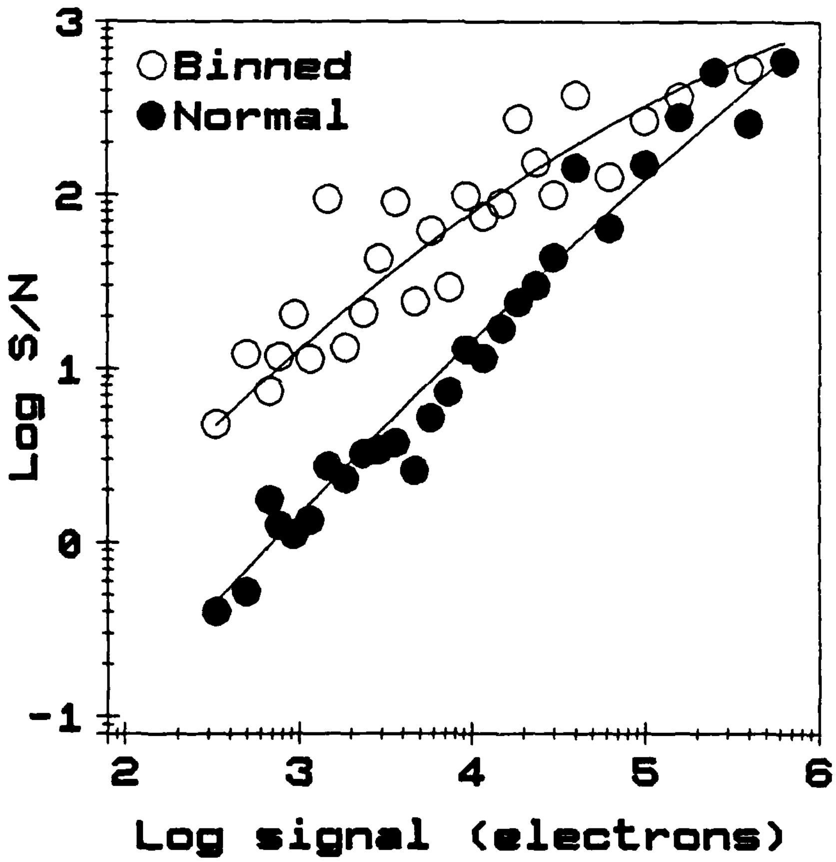
Serial shift
D
C
B
A
Parallel shift
1
2
3
A+B
Charge readout
C+D
4
5
6

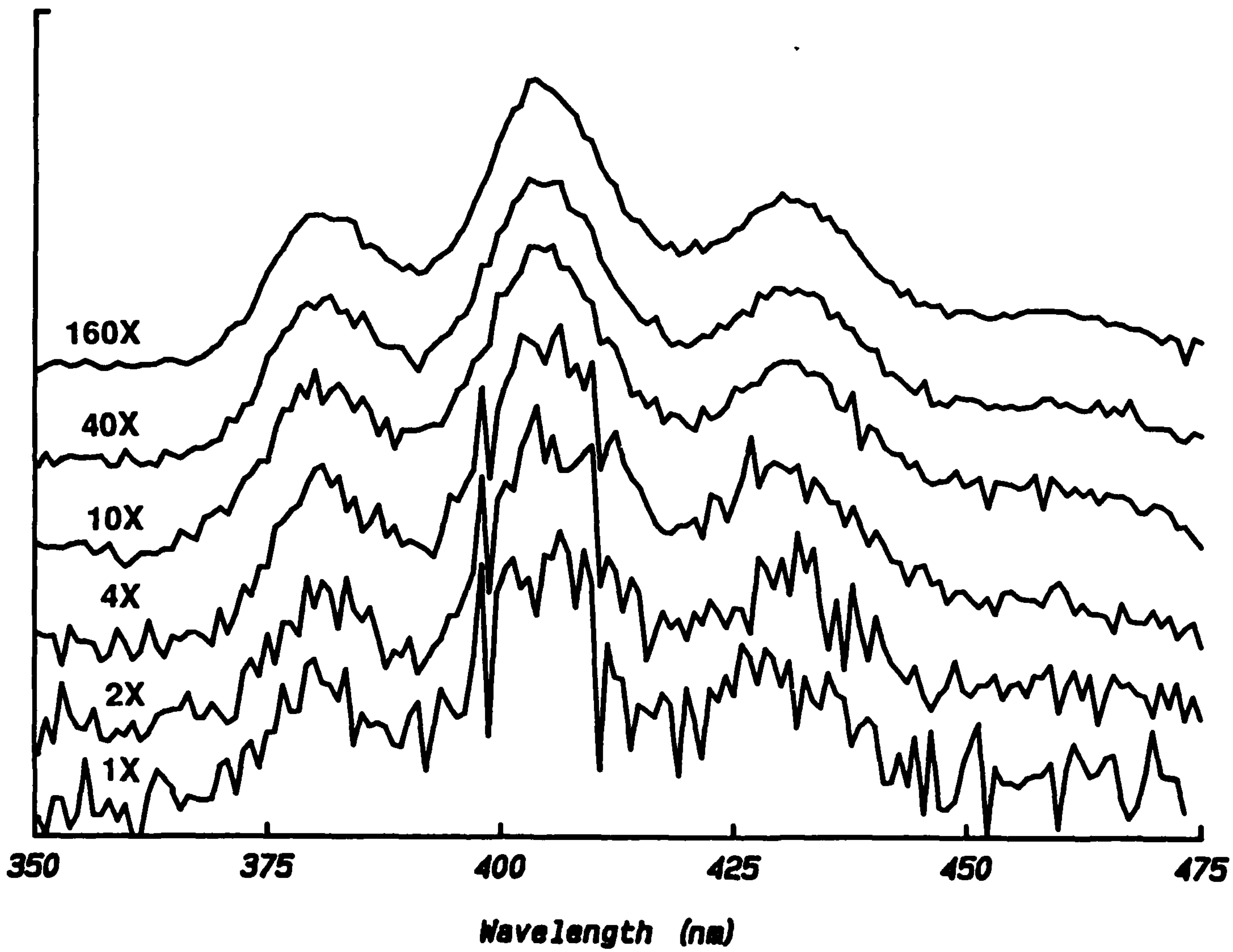


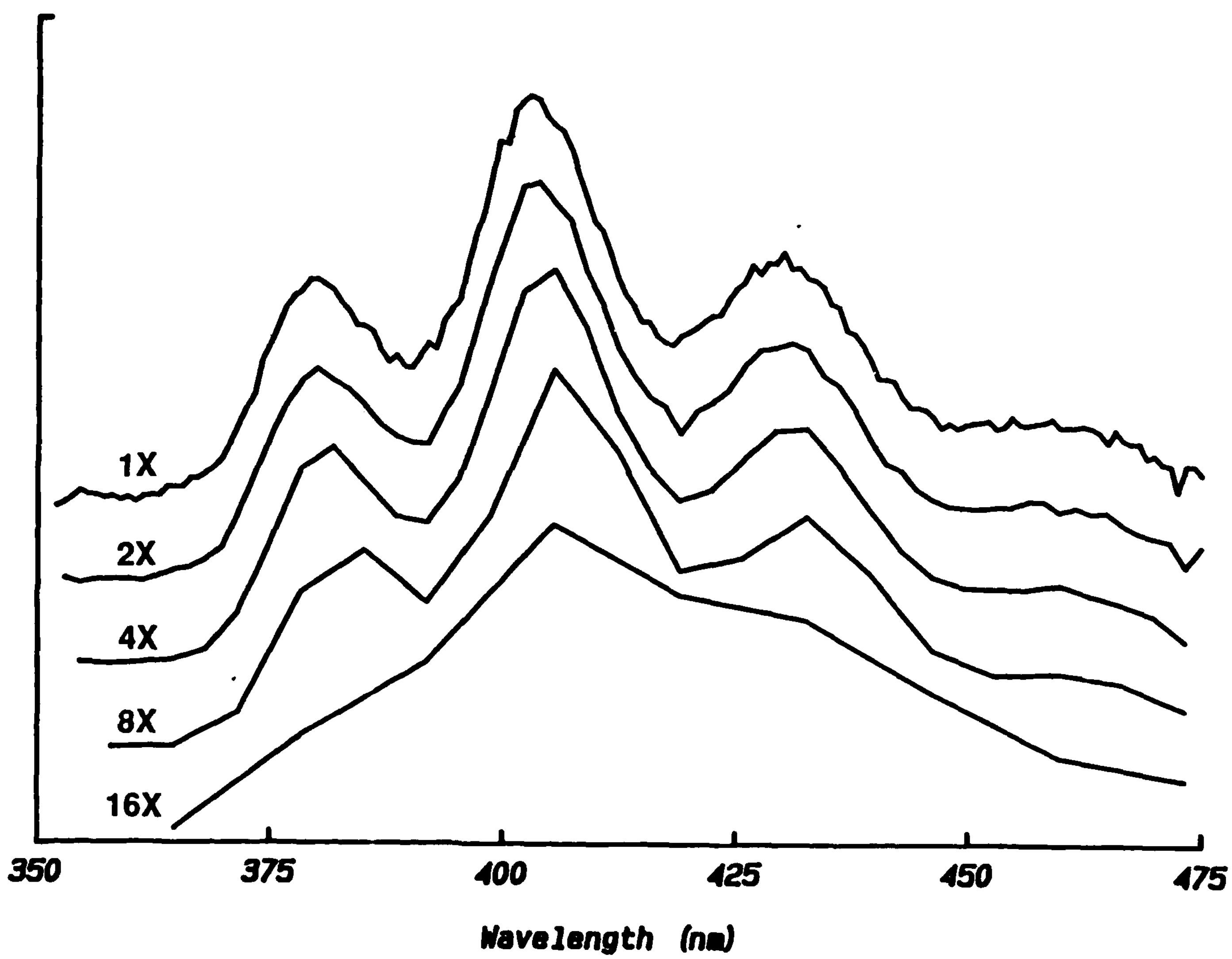
A
B
C
D
E
F
1
A+B
C
D
E
F
Parallel shift
3
A
B
C
D
E
F
Parallel shift
2
A+B+C
D
E
F
Parallel shift
4

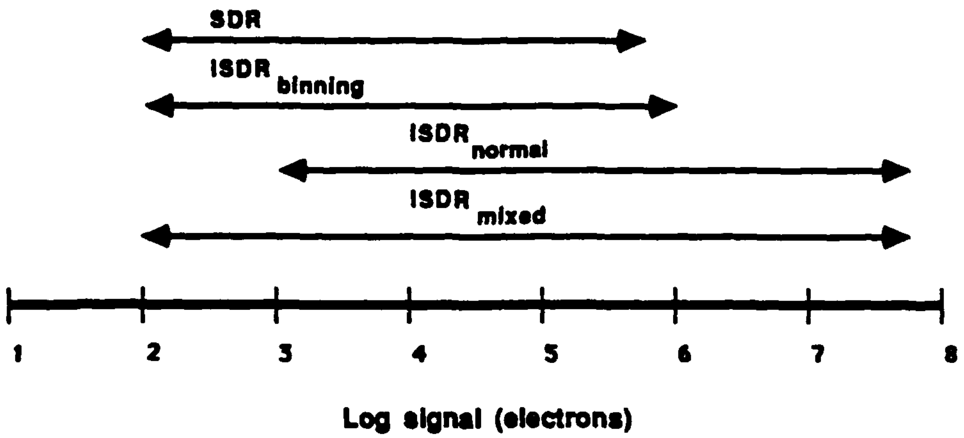

Grating
CCD
Dewar
Camera Head
Shutter
Camera
Controller
Computer
A
B
Hg Pen Lamp

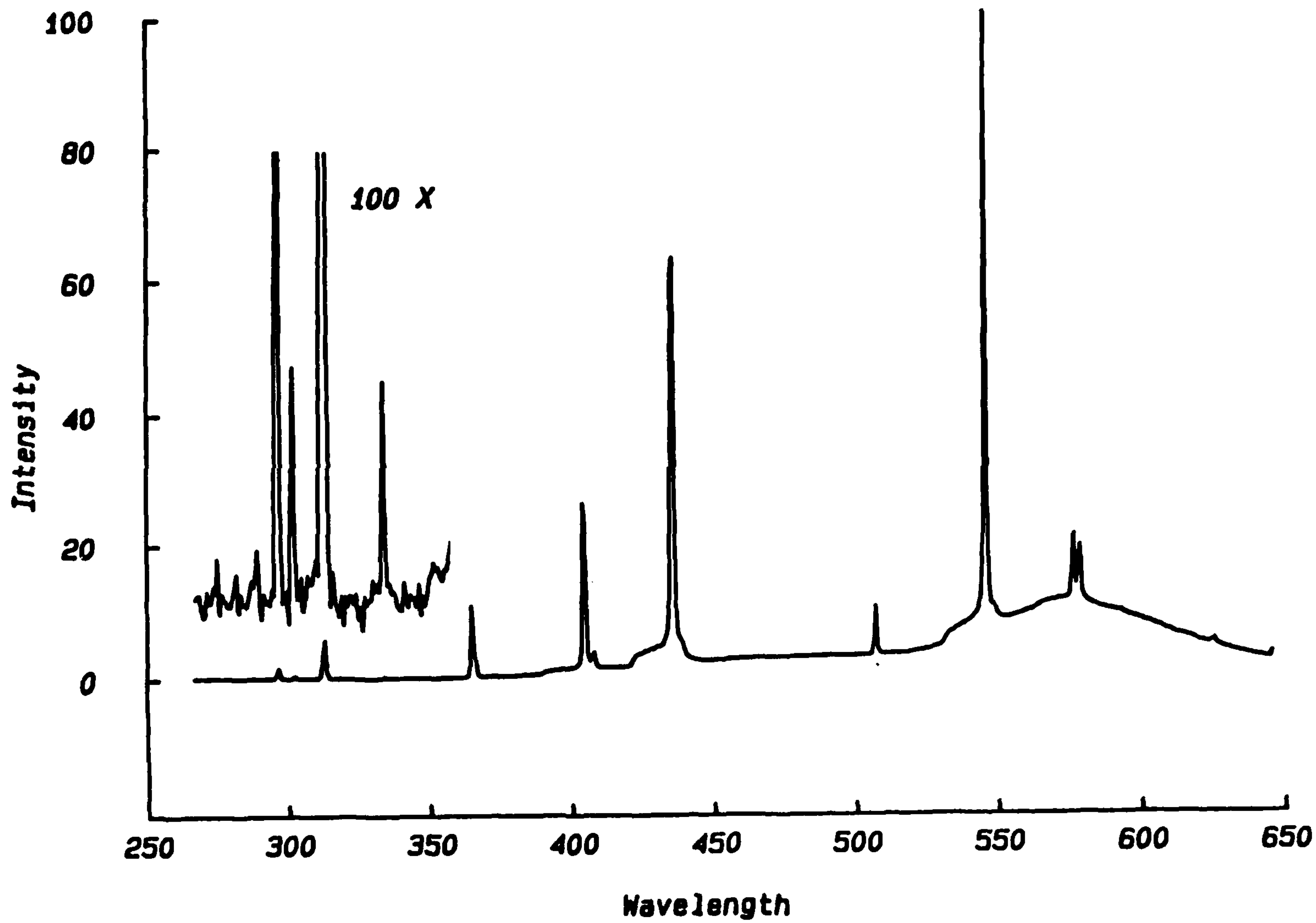

Serial Register
Slit
Wavelength
Parallel register
Parallel Orientation
Spectrum
Serial Register
Output node
On-chip amplifier
Wavelength
Slit
Parallel register
Serial Orientation


Binned
Normal
3
2
1
0
-1
Log S/N
2
3
4
5
6
Log signal (electrons)


160X
40X
10X
4X
2X
1X
350
375
400
425
450
475
Wavelength (nm)


1X
2X
4X
8X
16X
350
375
400
425
450
475
Wavelength (nm)


SDR
ISDR binning
ISDR normal
ISDR mixed
1
2
3
4
5
6
7
8
Log signal (electrons)


100 X
Intensity
100
80
60
40
20
0
250
300
350
400
450
500
550
600
650
Wavelength

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